

Search for Sterile Neutrinos at Long and Short Baselines

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Neutrino physics is currently suffering from lack of knowledge from at least four major ingredients. One of them is the presence or not of new sterile neutrino states at the mass scale of around 1 eV. Settling this point should be the highest priority for the neutrino community. We will discuss the state-of-the art of experimental searches for sterile neutrinos with accelerators, both at long and short baselines.

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1 Introduction

The current scenario of the Standard Model (SM) of particle physics, being arguably stalled by the discovery of the Higgs boson, is *desperately* looking for new experimental inputs to provide a more comfortable and *conformable* theory. In parallel, experiments on neutrinos so far have been an outstanding source of novelty and unprecedented results. In the last two decades several results were obtained by studying atmospheric, solar or reactor neutrinos, or more recently with neutrinos from accelerator-based beams. Almost all these results have contributed to strengthen the flavour-SM. Nevertheless, relevant parts like the values of the leptonic CP phase, δ_{CP} and the neutrino masses are still missing, a critical ingredient being the still undetermined neutrino mass ordering.

Furthermore, tensions still exist among some experimental results. As shown below, the most relevant concerns the existence or not of a non-standard neutrino state at the mass scale of 1 eV. These states, “sterile neutrinos” in the original definition of Bruno Pontecorvo in 1968 [1], reached the level of suggestive possibility since in the last years three different kinds of experiments hinted at their existence. The excess of ν_e ($\bar{\nu}_e$) observed originally by the LSND [2] collaboration and the (inconclusive) result by MiniBooNE [3] collaboration, as well as the so-called reactor [4] and Gallium [5, 6] neutrino anomalies can be coherently interpreted as due to the existence of at least a fourth sterile neutrino with a mass at the eV scale.

As a matter of fact both δ_{CP} and the mass ordering, together with the technical but relevant ingredient of the still undetermined amount of the deviation, with sign, of the *atmospheric* mixing angle, θ_{23} , from $\pi/4$, are tightly inter-connected to get a comprehensive description of the neutrino oscillation paradigm. As demonstrated very recently [7] these three parameters may depend on the further occurrence of neutrino sterile states at the 1 eV mass scale. Therefore, a clarification of the sterile issue is mandatory. A more detailed discussion of the past and current scenario can be found in [8].

The most critical point in the search for sterile states stays in the lack of any appearance/disappearance affecting ν_μ or ν_τ neutrinos. The set of results that addresses the neutrino anomalies read off by LSND *et al.* are all related to appearance/disappearance effects for ν_e and $\bar{\nu}_e$. There are actually phenomenological strong tensions when $3 + 1$ or $3 + n$ models are used to interpret the ν_e ($\bar{\nu}_e$) appearance/disappearance and the corresponding, required, appearance/disappearance of the other flavours, ν_μ and ν_τ [9].

In this report we will focus on the current experimental activity about the search for sterile neutrinos at 1 eV, based on accelerator ν_μ beams, either in a long-baseline or a short-baseline configuration.

2 Sterile neutrinos

The presence of an additional sterile-state can be expressed in the extended PMNS [1, 10] mixing matrix ($U_{\alpha i}$ with $\alpha = e, \mu, \tau, s$, and $i = 1, \dots, 4$). In this model, called “3+1”, the neutrino mass eigenstates ν_1, \dots, ν_4 are labeled such that the first three states are mostly made of active flavour states and contribute to the “standard” three flavour oscillations with the squared mass differences $\Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$ and $|\Delta m_{31}^2| \sim 2.4 \times 10^{-3} \text{ eV}^2$, where $\Delta m_{ij}^2 = m_i^2 - m_j^2$. The fourth mass eigenstate, which is mostly sterile, is assumed to be much heavier than the others, $0.1 \text{ eV}^2 \lesssim \Delta m_{41}^2 \lesssim 10 \text{ eV}^2$. The opposite case in hierarchy, i.e. negative values of Δm_{41}^2 , produces a similar phenomenology from the oscillation point of view but is disfavored by cosmological results on the sum of neutrino masses [11]*.

The phenomenology at short-baseline (SBL) is simplified since $L/E \sim 1 \text{ km/GeV}$. Thus the oscillation effects due to Δm_{21}^2 and Δm_{31}^2 can be neglected. Therefore the oscillation probability depends only on Δm_{41}^2 and $U_{\alpha 4}$ with $\alpha = e, \mu, \tau$. In particular the survival probability of muon neutrinos is given an the effective two-flavour oscillation formula:

$$P(\nu_\mu \rightarrow \nu_\mu)_{SBL}^{3+1} = 1 - [4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)] \sin^2 \frac{\Delta m_{41}^2 L}{4E}, \quad (1)$$

where $4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$ is the *amplitude* and, since the baseline L is fixed by the experiment location, the oscillation *phase* is driven by the neutrino energy E .

In contrast, appearance channels (i.e. $\nu_\mu \rightarrow \nu_e$) are driven by terms that mix up the couplings between the initial and final flavour-states and the sterile state, yielding a more complex picture:

$$P(\nu_\mu \rightarrow \nu_e)_{SBL}^{3+1} = 4|U_{\mu 4}|^2|U_{e 4}|^2 \sin^2 \frac{\Delta m_{41}^2 L}{4E} \quad (2)$$

Similar formulas hold also assuming more sterile neutrinos ($3 + n$ models).

Since $|U_{\alpha 4}|$ is expected to be small, the appearance channel is suppressed by two more powers in $|U_{\alpha 4}|$ with respect to the disappearance one. Furthermore, since ν_e or ν_μ appearance requires $|U_{e 4}| > 0$ and $|U_{\mu 4}| > 0$, it should be naturally accompanied by non-zero ν_e and ν_μ disappearances. In this sense the disappearance searches are essential for providing severe constraints on the theoretical models (a more extensive discussion on this issue can be found e.g. in Section 2 of [12]).

It should be also mentioned that a good control of the ν_e contamination is important when using the $\nu_\mu \rightarrow \nu_e$ for sterile neutrino searches at SBL. In fact the observed number of ν_e neutrinos would depend on both the $\nu_\mu \rightarrow \nu_e$ appearance and the $\nu_e \rightarrow \nu_s$ disappearance, from the ν_μ and ν_e components of the beam, respectively.

*Actually cosmology tends more and more even to disprove the NH case and therefore the existence of a relativistic specie at 1 eV mass.

On the other hand, the amount of ν_μ neutrinos would be affected by the $\nu_\mu \rightarrow \nu_s$ and $\nu_e \rightarrow \nu_\mu$ transitions. However the latter term (ν_μ appearance) would be much smaller than in the ν_e case since the ν_e contamination in ν_μ beams is usually at the percent level. We would thus conclude that oscillation probabilities in the ν_μ disappearance channel, in either a near or a far detector, are not affected by any interplay of different flavours. Since both near and far detectors measure the same individual disappearance transition, the probability amplitude should be the same at both sites.

The situation is quite more complicated in the long-baseline (LBL) configuration. When $L/E \gg 1$ km/GeV, that is the case for the Long-Baseline experiments, the two-flavour oscillation is not a good approximation. In the case of the CNGS beam, when studying the ν_τ oscillation rate the only valid approximations correspond to neglect the solar-driven term, i.e. $\Delta m_{21}^2 \sim 0$, and to discard the ν_e component of the beam. However when the $\nu_\mu \rightarrow \nu_e$ channel is studied the intrinsic ν_e beam-component becomes a non-negligible factor [13].

Considering the $(\nu_\mu, \nu_\tau, \nu_s)$ triplet, together with the above two approximations, the oscillation probability $\nu_\mu \rightarrow \nu_\tau$ can be written as:

$$\begin{aligned} P_{\nu_\mu \rightarrow \nu_\tau} = & 4|U_{\mu 3}|^2|U_{\tau 3}|^2 \sin^2 \frac{\Delta_{31}}{2} + 4|U_{\mu 4}|^2|U_{\tau 4}|^2 \sin^2 \frac{\Delta_{41}}{2} \\ & + 2\Re[U_{\mu 4}^* U_{\tau 4} U_{\mu 3} U_{\tau 3}^*] \sin \Delta_{31} \sin \Delta_{41} \\ & - 4\Im[U_{\mu 4}^* U_{\tau 4} U_{\mu 3} U_{\tau 3}^*] \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41} \\ & + 8\Re[U_{\mu 4}^* U_{\tau 4} U_{\mu 3} U_{\tau 3}^*] \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2} \\ & + 4\Im[U_{\mu 4}^* U_{\tau 4} U_{\mu 3} U_{\tau 3}^*] \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}, \end{aligned}$$

using the definition $\Delta_{ij} = 1.27 \Delta m_{ij}^2 L/E$ (i,j=1,2,3,4), with Δ_{31} and Δ_{41} expressed in eV², L in km and E in GeV. The first term corresponds to the standard oscillation, the second one to the pure exotic oscillation, while the last 4 terms correspond to the interference between the standard and sterile neutrinos. By defining $C = 2|U_{\mu 3}||U_{\tau 3}|$, $\phi_{\mu\tau} = \text{Arg}(U_{\mu 3}^* U_{\tau 3}^* U_{\mu 4}^* U_{\tau 4}^*)$ and $\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$, and noting explicitly the dependence of the probability on energy E , the expression can be re-written as:

$$\begin{aligned} P(E) = & C^2 \sin^2 \frac{\Delta_{31}}{2} + \sin^2 2\theta_{\mu\tau} \sin^2 \frac{\Delta_{41}}{2} \\ & + \frac{1}{2}C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin \Delta_{31} \sin \Delta_{41} \\ & - C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41} \\ & + 2C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2} \\ & + C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}, \end{aligned}$$

where interesting dependences rise up, namely the sign of Δm_{13}^2 (3^{rd} and 6^{th} terms) and CP-violating terms (4^{th} and 6^{th} terms). Finally, since at LBL $L/E \gg 1$ one can average over the energy obtaining $\langle \sin \Delta_{41} \rangle \approx 0$ and $\langle \sin^2 \frac{\Delta_{41}}{2} \rangle \approx \frac{1}{2}$. The following expression is pulled out:

$$\begin{aligned}
P(E) \simeq & C^2 \sin^2 \frac{\Delta_{31}}{2} + \frac{1}{2} \sin^2 2\theta_{\mu\tau} \\
& + C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \\
& + \frac{1}{2} C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin \Delta_{31}.
\end{aligned}$$

This formula indicates that we are sensitive to the effective sterile mixing angle, $\theta_{\mu\tau}$, the mass hierarchy (MH, Normal NH or Inverted IH) and to the new CP-violating phase.

3 OPERA preliminary results on sterile neutrinos from ν_τ and ν_e

What occurs in the long-baseline scenario is an evident interplay of interference effects, such that there are zones of phase-space ($\sin^2 2\theta_{\mu\tau}$, Δm_{41}^2) where more events are expected and zones where less events are expected. On top of that the mass hierarchy has to be disentangled. Therefore the method carried out by the OPERA collaboration is independently applied to the NH and IH cases. Maximization of the likelihood is performed over $\phi_{\mu\tau}$, C and $\theta_{\mu\tau}$, i.e the CP-violation phase and the two effective mixing angles of the 3^{rd} and 4^{th} mass-states with ν_μ and ν_τ , respectively.

Results on sterile limits based on four ν_τ candidates have been published by OPERA [14]. An updated analysis based on the just discovered 5^{th} candidate [15] was released last year [16]. Since OPERA sensitivity is limited to the region ($\sin^2 2\theta_{\mu\tau} \gtrsim 0.1$, $\Delta m_{41} \gtrsim 0.01 \text{ eV}^2$) its analysis was two-fold. In the first case the $\Delta m_{41} > 1 \text{ eV}^2$ region was considered, where almost no correlation with the effective mixing angle is present and the exclusion limit on the plane of the phase vs the mixing angle can be extracted (figure 1). When marginalization over the phase is made, the limit $\sin^2 2\theta_{\mu\tau} < 0.11$ at 90% C.L. is obtained (preliminary).

To extend the search for a possible fourth sterile neutrino down to small Δm_{41}^2 values, a second kind of analysis has been performed by OPERA using the GLOBES software, which takes into account the non-zero Δm_{12}^2 value and also matter effects, the Earth density being approximated by a constant value estimated with the PREM shell-model. This time the Δm_{31}^2 parameter has been profiled out (see [14] for more details and references). In figure 2 the preliminary 90% CL exclusion plot is reported in the Δm_{41}^2 vs $\sin^2 2\theta_{\mu\tau}$ parameter space. The most stringent limits of direct

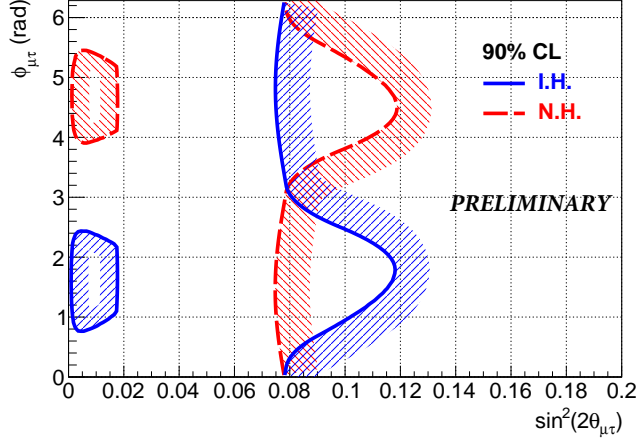


Figure 1: 90% C.L. exclusion limits in the $\phi_{\mu\tau}$ vs $\sin^2 2\theta_{\mu\tau}$ parameter space for normal (NH, dashed red) and inverted (IH, solid blue) hierarchies, assuming $\Delta m_{41}^2 > 1 \text{ eV}^2$. Bands are drawn to indicate the excluded regions.

searches for $\nu_\mu \rightarrow \nu_\tau$ oscillations at short-baselines obtained by the NOMAD [17] and CHORUS [18] experiments are also shown.

Another very interesting analysis is in progress in OPERA on the $\nu_\mu \rightarrow \nu_e$ search. The 2013 analysis [19] will be updated using the full data set and a much less approximate analysis as previously done. The preliminary selection is shown in table 1. The exclusion region will be set in the plane Δm_{41}^2 vs $\sin^2 2\theta_{\mu e}$.

	all energy range	$E < 20 \text{ GeV}$
ν_e candidates (30% data)	19	4
background (30% data)	19.2 ± 2.8	4.6
ν_e candidates (all data), preliminary	52	9

Table 1: The published selected ν_e candidates (and expected background) by OPERA, corresponding to the 30% of data sample and the preliminary selection on the full statistics.

4 MINOS and SuperK analyses

The MINOS and SuperK collaborations have also studied in detail the $\nu_\mu \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_e$ oscillations to exclude extra contributions from $\nu_\mu \rightarrow \nu_s$ oscillations. Recent results have been given by MINOS that makes use of the NuMI beam at FNAL [20],

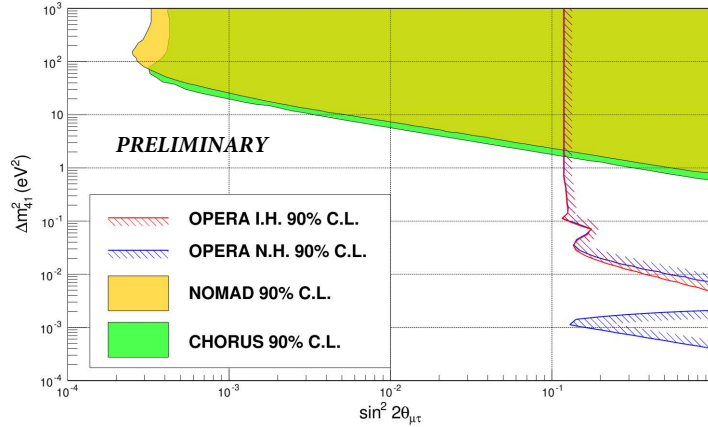


Figure 2: OPERA preliminary 90% C.L. exclusion limits in the Δm_{41}^2 vs $\sin^2 2\theta_{\mu\tau}$ parameter space for the normal (NH, red) and inverted (IH, blue) hierarchy of the three standard neutrino masses. The exclusion plots by NOMAD [17] and CHORUS [18] are also shown. Bands are drawn to indicate the excluded regions. It is intriguing that for NI life seems harder than for IH.

and SuperK by using the atmospheric neutrino flux [21]. MINOS is also analyzing the $\bar{\nu}$ running-mode data-sample and their updated analysis on $\nu_\mu \rightarrow \nu_e$ will be soon released.

The SuperK analysis is two-fold, considering either $|U_{e4}| = 0$ with matter effects or the full PMNS and discarding the matter effect. In the latter case a strong limit is obtained, $|U_{\mu 4}| < 0.04$ at 90% C.L., for $\Delta m_{41}^2 > 0.1 \text{ eV}^2$, for a total exposure of 282 kton-year.

5 Short-baseline experiments

In the short-baseline configuration life is *a priori* much easier. The two-flavour approximation is valid (see equations 1 and 2). However several concerns rise up. The right choices of detectors for more than one site, with an effective inter-calibration and overlap over a large interval of energies, to overcome either the systematical errors or the interplayed oscillations between all the components of the beam, is mandatory to achieve a full disentangling.

The new SBL project at Fermilab [22] owns an excellent program for the measurement of the still not well know cross-sections, with an excellent technology. However the use of only the technique of Liquid Argon, mainly due to better develop the detectors in view of the long-baseline experiment, DUNE, may not be sufficiently robust e.g. for the measurement of the ν_μ disappearance. The unique features of an experiment that would single out the behaviors of ν_μ and $\bar{\nu}_\mu$ [23] will unfortunately not

be available as the proposal was not approved by FNAL. The NESSiE experiment, with its exploitation of the charge measurement on event-by-event basis, would be able to provide a unique gain in sensitivity of more than one order of magnitude in the mixing angle, for both neutrino and anti-neutrino channels, also challenging the interpretation of the anomalies at 1 eV scale as due to an oscillation with new neutrino sterile states.

6 Conclusions and perspectives

The long-standing issue on the existence of sterile neutrino states at the eV mass scale can receive new relevant inputs from the accelerator Long-Baseline experiments, like OPERA, MINOS and SuperK. From one side LBL, owing to the large L/E values, can only look at the averaged oscillation pattern (lacking any oscillatory behavior of data). From the other side, the not-negligible interference between flavours introduces dependencies on the mass hierarchy and the CP-violation phase.

New results were recently published by the three collaborations, either on $\nu_\mu \rightarrow \nu_\mu$ disappearance or on the $\nu_\mu \rightarrow \nu_\tau$ appearance. All the results put stringent exclusion limits on the effective mixing angles between ν_μ/ν_τ and ν_s , so increasing the tension with the positive results on ν_e appearance/disappearance. With regards to ν_e , OPERA and MINOS+ will soon release reliable results with their large data-set, by properly taking into account the extended $3 + 1$ scenario.

In case of existence of a sterile neutrino at the eV mass-scale this situation points towards a rather low effective mixing angle, of the order of 1%, between sterile and the standard neutrino flavours. Therefore for any experiment/proposal aiming to provide new results it is mandatory to reach a sensitivity of that level. There is presently only one approved experiment for the Short-Baseline configuration with an accelerator beam, even if previous proposals were available and new ones are under scrutiny, e.g. at JPARC [24].

The sterile neutrino story has so far been developed either by trying to establish the hints (each at 2–3 σ level) on ν_e appearance/disappearance, or looking at flavour connected channels, like the ν_μ disappearance one. Within the next 2–3 years experiments on reactors and with radioactive sources can confirm or disprove the ν_e anomalies, while there is presently no reliable experiment [23] looking at the interference at the level of 1% mixing between sterile and μ/τ neutrino states other than the LBL ones. These however have no possibility to observe the oscillation pattern. Therefore, new specific experiments should be settled and approved, in case reactor/source current experiments would provide positive results.

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